

# ON THE INJECTION SPECTRUM OF RELATIVISTIC ELECTRONS IN HIGH-REDSHIFT RADIO GALAXIES

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## ABSTRACT

We point out that the remarkable linearity of the ultra-steep radio spectra of high redshift radio galaxies reflects a previously reported general trend for powerful radio galaxies, according to which the spectral curvature is lesser for sources having steeper spectra (measured near rest-frame 1 GHz). We argue based on existing theoretical and observational evidence that it is premature to conclude that the particle acceleration mechanism in sources having straight, ultra-steep radio spectra gives rise to an ultra-steep injection spectrum of the radiating electrons. In empirical support to this we show that the estimated injection spectral indices, available for a representative sample of 35 compact steep spectrum (CSS) radio sources are not correlated with their rest-frame (intrinsic) rotation measures, which are known to be typically large, indicating a dense environment, as is also the case for high- $z$  radio galaxies.

*Subject headings:* galaxies: active – galaxies:clusters: intracluster medium – galaxies: high-redshift – galaxies:ISM – galaxies:jets – radio continuum:galaxies

## 1. INTRODUCTION

A few decades ago it was noticed that radio galaxies having steeper decimetric spectra tend to appear optically fainter and smaller in radio angular size (Tielens, Miley & Willis 1979; Blumenthal & Miley 1979; Gopal-Krishna & Steppe 1981; see also, Pauliny-Toth & Kellermann 1968). Since then, ultra-steep radio spectrum ( $\alpha < -1.1$ ,  $S_\nu \propto \nu^\alpha$ ) has been exploited as a remarkably effective tool for finding high- $z$  radio galaxies (hereafter HzRGs; see the review by Miley & de Breuck 2008), although a few extremely distant radio galaxies with a normal radio spectrum have also been discovered (e.g., Jarvis et al. 2009; Lilly 1988).

Until the 1970s, sources having ultra-steep radio spectra were almost exclusively found in nearby rich clusters of galaxies (e.g., Slingo 1974a; b). This clear trend continues to be witnessed in much larger samples of radio galaxies (e.g., Bornancini et al. 2010). From early on, the association of such sources with denser galaxy environments has been attributed to radiative aging of the relativistic plasma in the radio lobes whose detectability, however, gets prolonged beyond about  $10^8$  yr due to an effective confinement by the pressure of the hot ambient gas, the intracluster medium: ICM (Baldwin & Scott 1973). Tielens et al. (1979) indeed drew a distinction between the low power Ultra Steep Spectrum Radio Sources (USSRS) found in nearby clusters and the radio luminous high- $z$  USSRS, by pointing out that the ultra-steep spectral index of the former was defined in the meter/decimeter wavelength range, while for the high- $z$  USSRS it referred to the decimeter regime.

Salient explanations suggested for the observed propensity of HzRGs to be USSRS are:

(a) Radio spectra of powerful RGs at medium redshifts

typically show a downward curvature (e.g., Laing, Riley & Longair 1983; also, Murgia et al. 2002; Kühr et al. 1981; Bornancini et al. 2007), as already reported for the well known powerful radio galaxies Cygnus A (e.g., Mitton & Ryle 1969) and 3C 295 (Kellermann, Pauliny-Toth & Williams 1969; Jones & Preston 2001). Therefore, ‘radio K-correction’ could be substantial and cause the radio spectra of HzRGs to appear steeper in a given radio-frequency band (e.g., Bolton 1966; De Breuck et al. 2000; Jarvis et al. 2004; see, however, Klammer et al. 2006; Miley & De Breuck 2008). The downward spectral curvature is expected to be even stronger for HzRGs, due to the increased inverse Compton losses in a much stronger cosmic microwave background (e.g., Rees & Setti 1970; Gopal-Krishna, Wiita & Saripalli 1989; Krolik & Chen 1991; Martinez-Sansigre et al. 2006). Some empirical evidence for this was reported, based on an analysis employing, for the first time, the *rest-frame* radio spectra of powerful radio galaxies (Gopal-Krishna 1988; also, van Breugel & McCarthy 1990; Athreya & Kapahi 1998). However, the alternative explanation invoking the correlation between spectral steepness and radio luminosity cannot at present be excluded (e.g., Pauliny-Toth & Kellermann 1968; Gopal-Krishna & Wiita 1990 and references therein, Krolik & Chen 1991). In this case, Malmquist bias could spuriously cause the correlation of ultra-steep radio spectrum with redshift (e.g., Blundell, Rawlings, & Willott 1999).

(b) The other possibility is that the radio spectra of HzRGs are intrinsically steeper because, like the USSRS in nearby clusters, the HzRGs too are aging in denser galaxy environments (see above). There is indeed growing evidence, e.g., from Ly- $\alpha$  imaging, that HzRGs are located in overdense regions in the early universe; they are often seen to be surrounded by proto-clusters (Miley & De Breuck 2008 and references therein). Another key evidence for the putative dense gaseous medium surrounding HzRGs comes from radio polarimetric measurements that often reveal very large rotation measures (RM) for the RGs with  $z > 2$ ; typical values of intrinsic RM are

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$> 500 \text{ rad.m}^{-2}$  (e.g., Carilli, Owen & Harris 1994; Carilli et al. 1997; Athreya et al. 1998; Pentericci et al. 2000).

(c) An alternative to the above suggestions, motivated by the dense environments of HzRGs combined with the remarkable straightness of their spectra from meter to centimeter wavelengths (§3), is that the particle acceleration process in their hot spots itself leads to abnormally steep energy spectra of the injected electrons (Athreya & Kapahi 1988; Klammer et al. 2006). In this paper we revisit this viewpoint.

## 2. DO HZRGs HAVE AN ULTRA-STEEP INJECTION SPECTRUM?

A potentially useful clue to the physical mechanism in HzRGs emerges from their similarity in radio luminosity and rotation measure to the, so called ‘compact steep spectrum’ (CSS) radio galaxies, suggesting that the two classes of radio galaxies arise from powerful jets propagating in dense environments (see below). Typically, the powerful CSS radio galaxies of Fanaroff-Riley class II (FR II, Fanaroff & Riley 1974) extend just on the galactic scale, i.e., no larger than  $\sim 15$  to  $20 \text{ kpc}$  and account for nearly 15 and 30 percent of the bright radio sources in samples selected at metre and decimetre wavelengths, respectively (Kapahi 1981; Peacock & Wall 1982; also, Gopal-Krishna, Preuss, & Schilizzi 1980; O’Dea 1998; Saikia et al. 2001). Radio polarimetry of CSS sources has revealed that their intrinsic RMs are typically very large (median around  $500 \text{ rad.m}^{-2}$ ), compared to the normal population of FR II radio galaxies which are more extended (e.g., Mantovani et al. 2009; also, O’Dea 1998; Rossetti et al. 2006). This reinforces the view that the jets in CSS RGs are still propagating through a considerably denser ambient medium, namely the interstellar medium (ISM) of the host galaxy, akin to the situation envisaged for HzRGs (§1). The question posed in this paper then translates to asking whether any evidence exists for the relativistic particles in CSS RGs to have an ultra-steep energy injection spectrum (i.e., much steeper than the canonical value which corresponds to  $\alpha = -0.5$  to  $-0.7$ )?

In this context, we note that Murgia et al. (2002) have presented detailed synchrotron modeling of the radio spectra of a fairly large set of 45 lobe-dominated, broadly symmetric double radio sources with sizes less than  $\sim 15 \text{ kpc}$ . The spectra used in their analysis of these CSS sources span a wide frequency range from 74 MHz to 230 GHz. Spectral flattening towards higher frequency is rarely observed in their sample and, typically, the spectra are seen to steepen with frequency, with spectral index changing by  $\Delta\alpha \sim 0.5$ . This is reminiscent of the spectral break observed near 2 GHz in the powerful CSS RG 3C 295 which is a  $\sim 5 \text{ arcsec}$  double radio source (e.g., Perley & Taylor 1991) identified with the central galaxy of a rich cluster at  $z = 0.46$  (see, Fig. 5 in Jones & Preston 2001). For their sample of 45 symmetric CSS RGs, Murgia et al. have further shown that the radio spectra are generally well fit by a synchrotron aging model with *continuous* injection of synchrotron plasma (Kardashev 1962; Kellermann 1964). The injection spectral indices,  $\alpha_{inj}$ , estimated in their analysis range between  $-0.35$  and  $-0.8$ , with a median value of  $-0.63$  (Table 1). Note that the range in  $\alpha_{inj}$  can be partly attributed to uncertainties in the analysis procedure. At

frequencies well above the spectral break, the spectral index steepens to values  $< -1$  and therefore the source would be readily classified as USSRS if the spectral measurements sampled mainly the steepened segment of the radio spectrum (e.g., due to the spectral bend having already drifted out of the radio window typically sampled; see, e.g., Murgia et al. 2002).

Thus, based on the above detailed spectral modeling, there is at present no credible evidence for an ultra-steep injection spectrum in symmetric CSS RGs and, by inference, also for HzRGs which too are radio powerful and situated in fairly dense environment (§1). This point is further examined below.

## 3. LINEARITY OF RADIO SPECTRA IN HZRGs

Given that the radio spectra of a large majority ( $\sim 70\%$ ) of powerful 3CR radio galaxies, which are located at moderate redshifts, show a progressive steepening with frequency (Laing et al. 1983), it seemed striking that the wide band (26 MHz – 10 GHz) radio spectrum is remarkably straight in the case of USSRS 4C+41.17, the first RG discovered with  $z > 3.5$  (Chambers, Miley & van Breugel 1990). More recently, this ‘anomaly’ came into sharp focus when a straight (single power-law) spectrum spanning the frequency range from  $\sim 1$  to  $18 \text{ GHz}$ , was shown to be a common feature of HzRGs with an ultra-steep radio spectrum (Klammer et al. 2006). From the striking lack of downward spectral curvature in HzRGs, Klammer et al. have surmised that the injection spectrum of radiating electrons might itself be abnormally steep in these sources, perhaps caused by their evolution inside an increasingly dense environment prevailing at higher redshifts (in which the first-order Fermi acceleration is expected to yield an steeper electron energy spectrum, cf. Athreya & Kapahi 1998). However, the evidence presented below provides no compelling reason to favor this rather radical explanation for the spectral straightness. The observed straight radio spectra of the USSRS may well be consistent with the usual synchrotron/inverse-Compton aging. Here it is interesting to recall an earlier analysis of the radio spectra of a complete set of 95 FR II radio galaxies, derived from the 3CR sample, in which it was found that the steepness of the spectral index (measured either at 1 or 2 GHz rest-frame) anti-correlates with the spectral curvature (Mangalam & Gopal-Krishna 1995). It follows that, while spectral steepening with frequency is typical for FR II RGs having normal spectral indices, as already reported e.g., by Laing et al. (1983), it becomes negligible for sources having  $\alpha_{1\text{GHz}}$  (or  $\alpha_{2\text{GHz}}$ )  $\lesssim -1.2$  (which indeed is also reflected in the recent findings of Klammer et al. 2006 for the specific case of USSRS). It is thus more plausible that the spectral break in these sources has already migrated to longer wavelengths, leaving an essentially straight spectrum measured shortward of meter wavelengths (see, also, Murgia et al. 2002). Thus, in our view, the empirical correlation reported by Mangalam & Gopal-Krishna (1995) suggests a simpler scenario for the common occurrence of straight (single power-law type) radio spectra of USSRS/HzRGs, as highlighted by Klammer et al. (2006). This explanation should work even better for HzRGs not only because of a relatively large radio K-correction, but also because of the faster propagation of the spectral break toward lower frequencies due to the steep rise in the inverse Compton

losses against the sharply increased cosmic microwave background at higher redshifts (see §1).

Although it is more likely that the jets in FR II sources terminate in relativistic shocks, we first consider the case of non-relativistic shocks. Quantitatively, the theoretical expectation for the electron energy index,  $s$  and the spectral index  $\alpha$  (where  $N(E) \propto E^{-s}$ ,  $\alpha = (1 - s)/2$ ) in non-relativistic shocks can be expressed in terms of the relation (Bell 1978, Longair 1994)

$$\alpha_{inj} = \frac{3}{2(1-r)} \quad \text{and} \quad r = \frac{v_1}{v_2}, \quad (1)$$

where  $r$  is the compression ratio at the shock and  $v_1$  and  $v_2$  are respectively the upstream and downstream velocities of the flow. This can be further expressed in terms of the upstream Mach number using the Rankine-Hugoniot jump conditions for a gas with polytropic index of 5/3 as

$$s = \frac{2(M^2 + 1)}{(M^2 - 1)}. \quad (2)$$

Relating dense environments to strong shock ( $M \gg 1$ ), it is known that this leads to an injection spectral index,  $\alpha_{inj}$ , of  $-0.5$ , or steeper, for jets with non-relativistic bulk velocities. However, an appropriate treatment in the *non-relativistic* limit of the bulk flow is given by Kirk & Schneider (1987) who consider the fluid to be a *relativistic* plasma. From Fig 3 of their paper, it is seen that the computed  $\alpha_{inj}$  lies close to 0.5 for  $v_1/c$  in the range 0.1 – 0.5. It is thus clear that in the non-relativistic regime of the bulk flow, much steeper injection spectra would need weak shocks ( $M \simeq 1$ ). However these are difficult to expect in the dense environments prevailing at high redshifts; see §2.

In the currently popular scenario for classical double radio sources (FR II), particle acceleration by the first order Fermi process largely occurs in the vicinity of the Mach disk (shock) where the directed outflow of the relativistic jet fluid terminates and gets partially thermalized. The same plasma, after crossing the shock, inflates a region of intense synchrotron emission called hot spot, which is separated from the ambient intergalactic gas by a contact discontinuity advancing at non-relativistic speed (Scheuer 1974; 1995; Falle 1991). There has been considerable debate on the bulk speed of the kiloparsec scale jets. A variety of observational results have strengthened the case for relativistic bulk speeds, e.g., the Laing-Garrington effect (Laing 1988; Garrington et al. 1988, Mullin, Riley & Hardcastle 2008). Likewise, Georganopolous & Kazanas (2003) have argued that jet speed in FR II sources remain relativistic all the way to the terminal hot spot. These estimates imply an upward revision of the bulk velocity from about  $0.6c$  inferred for kpc scale jets by Wardle & Aaron (2007).

An appropriate treatment of the first order Fermi acceleration of relativistic plasma with underlying *relativistic* bulk flow was also considered by Kirk & Schneider (1987) who generalized the same problem considered earlier by Blandford & Ostriker (1978) for non-relativistic bulk velocities. The essential result is displayed in Fig 5 of their paper which plots  $(3 - 2\alpha_{inj})$  against the upstream velocity,  $v_1$  (approximately the jet velocity). Taking  $v_1$  in the range of  $(0.9 - 1)c$ , as justified above, and interpolating

between the curves computed for the two models (with and without isotropization of pitch angles) yields a narrow range for  $\alpha_{inj}$  between  $-0.55$  and  $-0.65$ , with the latter value corresponding to the anisotropic case. This is in excellent agreement with the typical injection spectral index estimated empirically by Murgia et al. (2002) for their sample of CSS sources. On the other hand, for a jet velocity of  $0.8c$ , Fig 5 indicates that  $\alpha_{inj}$  can be as steep as  $-1.3$ , mirroring the claim of Athreya & Kapahi (1998) who hypothesize lower upstream (jet) velocities  $v_1$  in HzRGs due to their denser environment. However, the link between larger ambient density and bulk speed of the jet remains unclear within the canonical picture of FR II sources where a cocoon of relativistic plasma surrounds the relativistic jet and protects it from the ambient medium. As stated earlier, Georganopolous & Kazanas (2003) argue that the bulk speed even in kpc scale jets remains relativistic ( $v_1 \sim c$ ) all the way up to the shock preceding the terminal hot spot where most of the particle acceleration occurs (see, also, Mullin et al. 2008).

Interestingly, a denser ambient medium at high redshifts (e.g. Klammer et al. 2006) might even yield a flatter injection spectrum. This is because in the first order Fermi process, a higher ambient density would increase the probability  $P$  of the particles in the downstream to remain within the acceleration region, without enhancing the fractional energy gain per crossing (hence maintaining a constant  $\beta$ , where  $E = E_0\beta^k$  at the  $k$ th crossing as determined by the upstream and downstream velocities; Bell 1978, Longair 1994). Heuristically, it means here that  $s = 1 - d \ln P / d \ln \beta$  would decrease, implying a flatter  $\alpha_{inj}$ . Thus, at least on theoretical grounds there appears to be no compelling reason to expect a steeper  $\alpha_{inj}$  due to a denser ambient medium.

We next look for any empirical clue to test the suggestion that first-order Fermi acceleration operating within the hot spots of FR II radio sources injects a steeper electron energy spectrum if the jets are expanding against a denser ambient medium. We shall employ the empirically determined quantity, rotation measure (RM), which is also widely used as an indicator of the ambient density. It is known that very high RMs are common for HzRGs (see above) and also for radio sources residing in the cores of cooling flow clusters (e.g., Carilli & Taylor 2002; Clarke et al 2001; Taylor, Barton & Ge 1994). Thus, based on the plausible premise that a large RM is a reliable indicator of a dense environment, we proceed to check if indeed the denser ambient medium associated with CSS RGs results in a steeper injection spectrum of relativistic electrons in their hot spots. For the 45 FR II CSS RGs in the Murgia et al. (2002) sample (§1), for which  $\alpha_{inj}$  values have been estimated in their study, we have carried out a literature search to obtain RM values. The search was successful for 35 of the total 45 sources and those estimates are listed in Table 1. The corresponding diagram showing the intrinsic (rest-frame) values of  $RM_{int} = RM (1+z)^2$  against  $\alpha_{inj}$  is displayed in Fig. 1. We believe this subset of 35 sources to be representative of the parent sample of 45 CSS RGs (since the availability of RM estimate in the literature was our sole criterion for deriving the subset).

From Fig. 1 no conspicuous trend is apparent to sup-

TABLE 1  
PARAMETERS OF THE 35 CSS SOURCES WITH KNOWN RM

Source Name	z	$\alpha_{inj}$	$ RM $ rad/m <sup>2</sup>	Error (RM)	$ RM_{int} $ rad/m <sup>2</sup>	Ref. code
0127+23	1.46	-0.76	105	590	635.4	b
0134+32	0.37	-0.5	79	...	148.3	a
0221+67	0.31	-0.56	1	...	1.7	a
0316+16	1.00	-0.81	246	6	984	g
0345+33	0.24	-0.58	339.1	9.2	521.4	h
0429+41	1.02	-0.49	1813	47	7397.8	b
0518+16	0.76	-0.47	1	...	3.1	a
0538+49	0.55	-0.44	1648	117	3959.3	b
0740+38	1.06	-0.75	40	11.3	169.7	c
0758+14	1.2	-0.79	114	14	551.8	g
1005+07	0.88	-0.57	141	5	498.3	d
1019+22	1.62	-0.77	18	20	123.5	d
1203+64	0.37	-0.66	86	11	161.4	d
1250+56	0.32	-0.39	93.7	8.5	163.3	h
1328+30	0.85	-0.38	0	1	0	i
1328+25	1.06	-0.47	148	...	628	a
1416+06	1.44	-0.5	42.5	0.8	253.0	c
1443+77	0.27	-0.64	24	13	38.7	g
1447+77	1.13	-0.62	57	10	258.6	d
1458+71	0.9	-0.65	60	...	216.6	a
1517+20	0.75	-0.69	498	...	1525.1	a
1607+26	0.47	-0.71	16	2.5	34.6	h
1634+62	0.99	-0.65	21.9	10.5	86.7	h
1637+62	0.75	-0.62	186.7	16.1	571.8	h
2248+71	1.84	-0.69	49	2	395.2	d
2249+18	1.76	-0.72	88	...	670.3	a
2252+12	0.54	-0.62	68	...	161.3	a
0809+404	0.55	-0.53	164.9	15.9	396.2	f
1025+390B	0.361	-0.65	41.7	3.3	77.2	f
1233+418	0.25	-0.51	10	...	15.6	e
1350+432	2.149	-0.84	152	...	1507.3	e

REFERENCES. — a- Mantovani et al. (2009); b- Inoue et al. (1995); c- Oren & Wolfe (1995); d- Simard-Normandin et al. (1981); e- Fanti et al. (2004); f- Klein et al. (2003); g- Broten et al. (1988); h- Tabara & Inoue (1980); i- Conway et al. (1983)

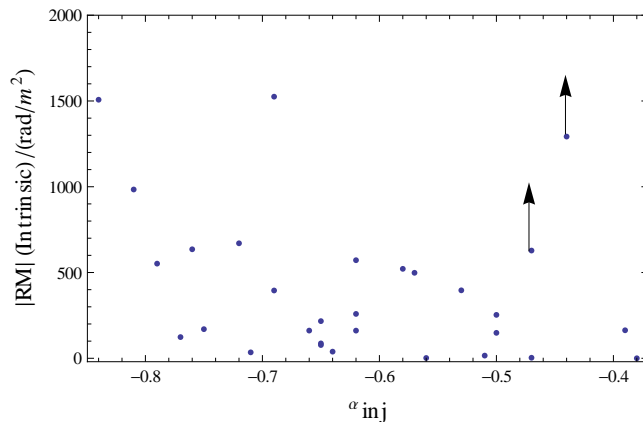


FIG. 1.— Scatter diagram of the rest-frame rotation measure vs the injection spectral index  $\alpha_{inj}$  for the set of 35 CSS sources. The two outliers are shown with arrows and have been shifted downwards by 1110 units.

port the case that a higher RM should correlate with a steeper injection spectrum of the radiating particles. The Spearman rank correlation test gives a correlation coefficient of just 0.132, amounting to a  $p$ -value (from the student  $t$  distribution) of 0.24, supporting the null hypothesis that  $\alpha_{inj}$  is uncorrelated with  $RM_{int}$ . Also, using a Fisher transformation to find the significance and

applying the result to the Normal distribution, the probability that they are uncorrelated turns out to be 0.83.

Thus, the evidence emerging from this admittedly limited, (but expectedly representative) sample does not support the assertion that steeper *injection spectra* are generic to high- $z$  radio galaxies. Given the importance of this issue, it would be valuable to extend the RM and radio spectral measurements to larger samples of CSS and HzRG sources.

#### 4. CONCLUSIONS

Using both observational and theoretical perspectives about classical double radio sources, we have argued that the straightness of ultra steep radio spectra of HzRGs, highlighted by Klamer et al. (2006), is likely to manifest the late stage of radio spectral evolution, instead of an ultra steep injection spectrum of the relativistic electron population. The latter possibility has been favored by some authors in view of the likelihood of HzRGs residing in denser environment compared to moderately distant FR II radio galaxies (see Klamer et al. 2006, Athreya & Kapahi, 1998). In the context of such FR II sources, the theory of first-order Fermi acceleration at relativistic shocks compressing relativistic jet fluid, could indeed yield a very steep injection spectrum ( $\alpha_{inj} < -1.3$ ) for upstream bulk speeds of  $\leq 0.8c$ . However, on theoretical grounds, such modest speeds are not favored for the large-scale jets typical of HzRGs (e.g., Wang et al. 2011). Also, the well-known association of ultra-steep radio spectrum with cluster radio sources is widely interpreted in terms of prolonged synchrotron losses enabled by a dense ambient intra-cluster medium whose presence is independently inferred from their very large RM values (Clarke et al. 2001; Carilli & Taylor 2002).

Interestingly, very large RM values are also found to occur for another class of FR II radio galaxies called ‘Compact Steep Spectrum’ (CSS) sources which too are therefore believed to lie in dense environments. We have highlighted a study of 45 CSS sources by Murgia et al. (2002) in which they have modelled the radio spectra and found  $\alpha_{inj}$  to lie in the range  $-0.35$  to  $-0.8$ , with a median value of  $-0.63$ . We have shown here that the intrinsic rotation measures of these sources do not correlate with  $\alpha_{inj}$  as estimated by Murgia et al. (2002). Thus, on balance, the observed remarkable straightness of the ultra-steep radio spectra of HzRGs, instead of being an outcome of very steep injection spectra, is more likely because the spectral bend caused by radiative losses has drifted out of the standard radio window to sub-GHz frequencies. Such an interpretation would also be consistent with the empirical finding that for FR II radio galaxies, in general, a steeper radio spectrum at decimeter wavelengths is anti-correlated with spectral curvature (Mangalam & Gopal-Krishna 1995).

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